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COLLISION AVOIDANCE STRATEGY FOR UNMANNED UNDERWATER VEHICLES USING CUBIC BÉZIER SPIRALS

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Abstract. *The oceans are of great economic importance for they are source of energetic resources (oil and gas); they are used for transportation of goods and passengers, and for allowing intercontinental communication through underwater cables. The hazards and costs associated with oceanic operations are very high, which makes attractive the research and development of Unmanned Underwater Vehicles (UUVs) increasingly more autonomous, safe and reliable Adverse situations occur when obstacles are detected in the UUV trajectory, thus adequate path planning and collision avoidance are directly related to the success of UUV missions. The subject of this work is collision avoidance with unmapped obstacles for UUVs. The proposed strategy for collision avoidance uses cubic Bézier spirals in order to generate a path that satisfies the kinematic constraints of the UUV.*

Keywords: *Path planning, obstacle avoidance, Bézier spirals, unmanned underwater vehicles*

1. INTRODUCTION

The oceans and seas cover approximately 70% of our planet's surface, and about 37% of the world's population lives within 100 km from an ocean (Yuh, 2000). Besides the indisputable importance towards the maintenance of life on the planet, the exploration of natural resources is of great economic and social importance. Despite it, very little is known about oceans and seas (Rocha, 2012).

Oceans are considered very important sources of energetic resources, such as oil and gas. Their surface is used for the transport of goods and passengers, and is of great importance for global economy. The intercontinental communication is largely achieved through submarine cables laid on the sea bed. The sea bed is also target of studies about the possibility of mineral resources exploration (Rocha, 2012).

The risks and costs involved in underwater operations draw attention towards the research and development of Unmanned Underwater Vehicles (UUVs) (Rocha, 2012).

During underwater operations, adverse situations occur when obstacles are detected in the UUV path, thus the adequate path planning is directly related to the mission success. This paper addresses the problem of collision avoidance with previously unmapped obstacles.

UUVs have kinematic and dynamic constraints that must be incorporated into the path planning process. If a path does not satisfy the kinematic and dynamic constraints of the UUV, there will be large tracking errors when the vehicle tries to follow this path (Choi, et al., 2008). In this paper the vehicle's constraints are summarized as the maximum curvature κ_{max} it is able to achieve. As long as the curvature of the path is equal to or smaller than κ_{max}, the vehicle's constraints are being satisfied.

This paper proposes a simple strategy avoiding collision with previously unmapped obstacles, while satisfying the vehicle's kinematic and dynamic constraints.

In section 2 is presented a brief review of path planning and collision avoidance for mobile robots, not only UUVs. In section 3 is presented in more details the G^2 continuous cubic Bézier spiral. Section 4 details the collision avoidance strategy to be proposed in the paper. Section 5 presents some results obtained using the proposed strategy. Section 6 presents a brief discussion about the results and the proposed strategy. The section 7 concludes the paper and presents some suggestions for future work.

2. PATH PLANNING AND COLLISION AVOIDANCE FOR MOBILE ROBOTS

In a general way, the path planning problem consists in determining a sequence of configurations that a robot or vehicle must assume in order to complete the proposed mission. In the specific case of underwater vehicles the path is defined as a set of waypoints that have to be reached in sequence (Paull, et al., 2013).

The path planning depends on many factors, such as information level about the environment, the quality wanted for the trajectory, and the mission objectives. If the ambient is static and a lot of information is available, the planning process may be slow without further consequences. On the other hand, if the environment is dynamic and/or unknown, the process must be fast enough to be made in real time (Paull, et al., 2013).

The paths generated by many popular strategies, such as cellular decompositon, visibility graph, Voronoi diagram, consist in a discrete set of points. Depending on the kinematic and dynamic constraints of the vehicle, it may not be possible for the vehicle to accurately follow these paths. A better strategy for these cases is to embed the kinematic and dynamic constraints to the path generation process (Jung and Tsiotras, 2008).

Considering a vehicle moving in a bidimensional plane with constant speed and finite turn-rate, the shortest path between two or more configurations is composed of circle arcs connected by a straight line. This path is called Dubins path (Owen, et al., 2014). Dubins paths are easily implemented; however they have a great disadvantage of not being curvature continuous, which cause positioning errors in the vehicle following them (Scheuer & Fraichard, 1997).

The path generation problem may be formulated including a continuous curvature constraint. The generated path is composed of a concatenation of clothoids, circle arcs and straight lines (Scheuer & Fraichard, 1997). These paths are not easily implemented because there is no closed form solution for clothoids, thus requiring an iterative solution (Tsourdos, et al., 2011).

Another solution to this problem is through the interpolation of a discrete set of points using splines or other parametric curves. For such it is usually necessary to solve an optimization problem including the kinematic constraints of the vehicles and the obstacles to be avoided. The advantage of using splines is that the whole path may be represented using few parameters (Jung and Tsiotras, 2008).

In (Sprunk, 2008) is proposed the use of Quintic Bézier Splines to solve the trajectory generation problem. In the work is conducted an explicit velocity planning along the vehicle's trajectory, which is a requirement for the inclusion of kinematic and dynamic constraints in the process of trajectory generation. It is used a feed forward controller capable of smoothly updating the trajectory, as a manner of dealing with previously unmapped obstacles.

The work of (Choi, et al., 2008) presents two algorithms for path planning for autonomous vehicles based on Bézier curves. Both algorithms join cubic Bézier curves segments, generating a smooth path that satisfies the vehicle constraints. The work also discusses the constrained optimization problem that optimizes the generated path according to a previously defined function.

The work of (Gilimyanov and Rapoport, 2013) develops a method to deform a preplanned path as a way of avoiding collision with an obstacle that moved or that have not been detected before. The developed method is based on the curvature smoothing of a B-spline through small variations in its control points. The smoothing is achieved through the minimization of the norm of a vector that describes a jump of the third derivative of the B-spline. The variations are found minimizing an objective function containing the square of the norm of the vectors and a penalty term for big variations in the objective function. The collision avoidance is achieved through the incorporation of a repulsive potential in the objective function.

The work of (Yang and Sukkarieh, 2010) presents an analytic algorithm to smoothing a piecewise linear path, satisfying a maximum curvature constraint. The algorithm is based on cubic Bézier spirals, called in the work as G2CBS. The algorithm is computationally inexpensive and easily implemented.

In this paper a simple strategy for collision avoidance will be devised. Within the studied works, the work of (Yang & Sukkarieh, 2010) is the most promising, mainly due to its simplicity. The G2CBS is shown in more details in the following section.

3. G² CONTINUOUS CUBIC BÉZIER SPIRAL (G2CBS)

As shown in (Yang and Sukkarieh, 2010) the curve with continous curvature that satisfies the maximum curvature constraint is obtained through the concatenation of two cubic Bézier spirals. Figure 1shows the resulting curve.

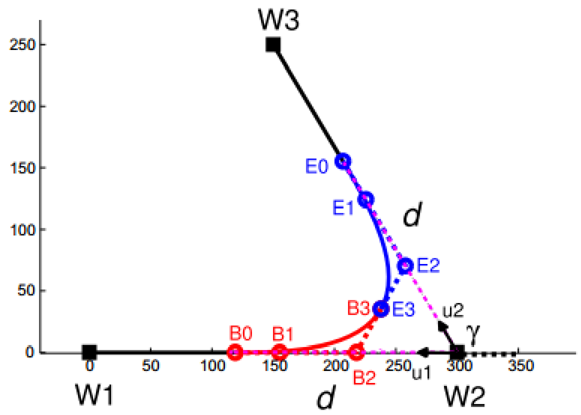

Figure 1 - G² continous cubic Bézier spiral path smoothing (Yang, et al., 2013)

For a specified maximum curvature κ_{max}, the control points of the spirals are given by the following equations:

$$\mathbf{B_0} = \mathbf{W_2} + d\mathbf{u_1} \quad (1)$$

$$\mathbf{B_1} = \mathbf{B_0} - g\mathbf{u_1} \quad (2)$$

$$\mathbf{B_2} = \mathbf{B_1} - h\mathbf{u_1} \quad (3)$$

$$\mathbf{B_3} = \mathbf{B_2} + k\mathbf{u_d} \quad (4)$$

$$\mathbf{E_0} = \mathbf{W_2} + d\mathbf{u_2} \quad (5)$$

$$\mathbf{E_1} = \mathbf{E_0} - g\mathbf{u_2} \quad (6)$$

$$\mathbf{E_2} = \mathbf{E_1} - h\mathbf{u_2} \quad (7)$$

$$\mathbf{E_3} = \mathbf{E_2} + k\mathbf{u_d} \quad (8)$$

where:

$$\mathbf{u_1} = (\mathbf{W_1} - \mathbf{W_2}) / ||(\mathbf{W_1} - \mathbf{W_2})|| \quad (9)$$

$$\mathbf{u_2} = (\mathbf{W_3} - \mathbf{W_2}) / ||(\mathbf{W_3} - \mathbf{W_2})|| \quad (10)$$

$$\mathbf{u_d} = (\mathbf{E_2} - \mathbf{B_2}) / ||(\mathbf{E_2} - \mathbf{B_2})|| \quad (11)$$

$$g = c_1 c_3 d \quad (12)$$

$$h = c_3 d \quad (13)$$

$$k = 6 c_3 d / (c_1 + 4) \quad (14)$$

$$c_1 = 2(-1+\sqrt{6}) / 5 \quad (15)$$

$$c_2 = 7{,}2364 \quad (16)$$

$$c_3 = (c_1 + 4) / (c_2 + 6) \quad (17)$$

$$c_4 = (c_1 + 4)^2 / (54 c_3) \quad (18)$$

$$d = (c_4 \tan(\gamma/2)) / (\kappa_{max} \cos(\gamma/2)) \quad (19)$$

$$\gamma = \arccos((\boldsymbol{W_2} - \boldsymbol{W_1})(\boldsymbol{W_3} - \boldsymbol{W_2}) / (\|(\boldsymbol{W_2} - \boldsymbol{W_1})\| \, \|(\boldsymbol{W_3} - \boldsymbol{W_2})\|)) \tag{20}$$

In (Yang and Sukkarieh, 2010) are found more details of how are obtained the parameters used for calculating the control points of the Bézier spirals.

4. STRATEGY FOR COLLISION AVOIDANCE

The strategy to be proposed in this paper is to generate waypoints around the obstacle and then use G2CBS to join then, thus obtaining a smooth path that satisfies the vehicle kinematic constraints.

4.1 Proposed Strategy

The necessary data for the implementation of the strategy are: a set of waypoints, $\boldsymbol{W_i}$, $\boldsymbol{W_f}$, $\boldsymbol{W_h}$, $\boldsymbol{W_g}$, and the maximum curvature κ_{max}.

The vehicle is considered a point moving in the plane and its speed is constant. A circular obstacle is considered. The radius of the obstacle must incorporate a safety margin, so the vehicle effectively avoids colliding with it.

The proposed strategy consists in:

a. Find the contact points ($\boldsymbol{Pc_1}$ and $\boldsymbol{Pc_2}$) between the initial trajectory and the obstacle;
b. Find the two points on the circle where the derivative is parallel to the initial trajectory ($\boldsymbol{Pt_1}$ and $\boldsymbol{Pt_2}$);
c. Calculate the distance d_p between $\boldsymbol{Pt_1}$ and $\boldsymbol{Pt_2}$ and the initial trajectory and chose the point with the smaller d_p;
d. Calculate the middle point $\boldsymbol{Pm_i}$ between $\boldsymbol{W_i}$ and $\boldsymbol{Pc_1}$;
e. Calculate

$$\gamma m_i = \arctan(2d_p / \| \boldsymbol{Pm_i} - \boldsymbol{W_i} \|) \tag{21}$$

f. Calculate dm_i using Eq. (19) and γm_i;
g. Repeat the steps d, e and f using $\boldsymbol{W_f}$ and $\boldsymbol{Pc_2}$;
h. Calculate

$$d_{\pi/2} = c_4 \sqrt{2} / \kappa_{max} \tag{22}$$

i. Calculate the intermediary waypoints using the following equations:

$$\boldsymbol{W_0} = \boldsymbol{Pc_1} - \min((d_{\pi/2} + a_i - \| \boldsymbol{Pc_2} - \boldsymbol{Pc_1} \|/2) , (\| \boldsymbol{Pc_1} - \boldsymbol{W_i} \|/2))\cdot\boldsymbol{u} \tag{23}$$

$$\boldsymbol{W_1} = \boldsymbol{Pt} - a_i\cdot\boldsymbol{u} \tag{24}$$

$$\boldsymbol{W_2} = \boldsymbol{Pt} + a_i\cdot\boldsymbol{u} \tag{25}$$

$$\boldsymbol{W_3} = \boldsymbol{Pc_2} - \min((d_{\pi/2} + a_f - \| \boldsymbol{Pc_2} - \boldsymbol{Pc_1} \|/2) , (\| \boldsymbol{W_f} - \boldsymbol{Pc_2} \|/2))\cdot\boldsymbol{u} \tag{26}$$

where:

$$a_i = \min(\| \boldsymbol{Pc_2} - \boldsymbol{Pc_1} \|/2 , dm_i) \tag{27}$$

$$a_f = \min(\| \boldsymbol{Pc_2} - \boldsymbol{Pc_1} \|/2 , dm_f) \tag{28}$$

$$\boldsymbol{u} = (\boldsymbol{W_f} - \boldsymbol{W_i}) / \|(\boldsymbol{W_f} - \boldsymbol{W_i})\| \tag{29}$$

j. Calculate

$$\eta = \arccos((\boldsymbol{W_h} - \boldsymbol{W_i})(\boldsymbol{W_f} - \boldsymbol{W_i}) / (\|(\boldsymbol{W_h} - \boldsymbol{W_i})\| \, \|(\boldsymbol{W_f} - \boldsymbol{W_i})\|)) \tag{30}$$

k. Calculate d_η using Eq. (19) and η. If $\boldsymbol{W_h}$ does not exist, d_η is zero;

l. Check

$$|| \boldsymbol{W_0} - \boldsymbol{W_i} || < (dm_i + d_\eta) \tag{31}$$

if it is true, the algorithm will fail in finding a path for the specified κ_{max};

m. Calculate

$$\alpha = \arccos((\boldsymbol{W_f} - \boldsymbol{W_3})(\boldsymbol{W_g} - \boldsymbol{W_f}) /(||(\boldsymbol{W_f} - \boldsymbol{W_3})|| \, ||(\boldsymbol{W_g} - \boldsymbol{W_f})||)) \tag{32}$$

n. Calculate d_α using Eq. (19) and α. If $\boldsymbol{W_g}$ does not exist, d_α is zero;

o. Check

$$|| \boldsymbol{W_f} - \boldsymbol{W_3} || < (dm_f + d_\alpha) \tag{33}$$

if it is true:

   a. Remove $\boldsymbol{W_3}$;
   b. Repeat steps m, n and o, using $\boldsymbol{W_2}$ instead of $\boldsymbol{W_3}$;
   c. If the inequality is true, the algorithm will fail in finding a path for the specified κ_{max};

p. Smooth the piecewise linear path using G2CBS.

The steps from a. to i. generate the intermediary waypoints around the obstacle, while the steps from j. to o. check if the resulting path is feasible. Figure 2 illustrates the process.

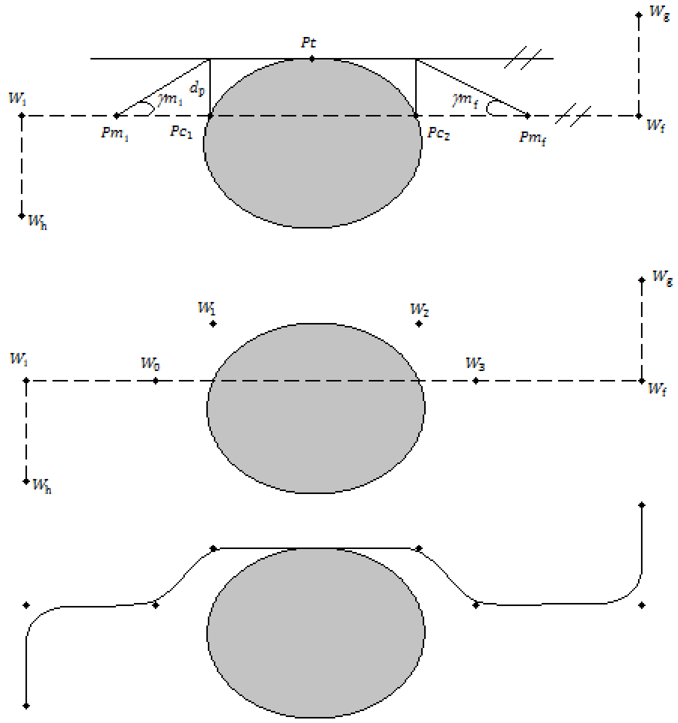

Figure 2 – Strategy for collision avoidance

5. SIMULATIONS

The software MATLAB was used for simulating five different cases. In every case there are several waypoints scattered across the plan, only one circular obstacle with radius of 5 meters and 1 meter of safety margin. The maximum curvature is 0,5 m^{-1}, except for Case V where it is 1 m^{-1}. It is presented the curvature along the trajectory only for Case I.

5.1 Case I

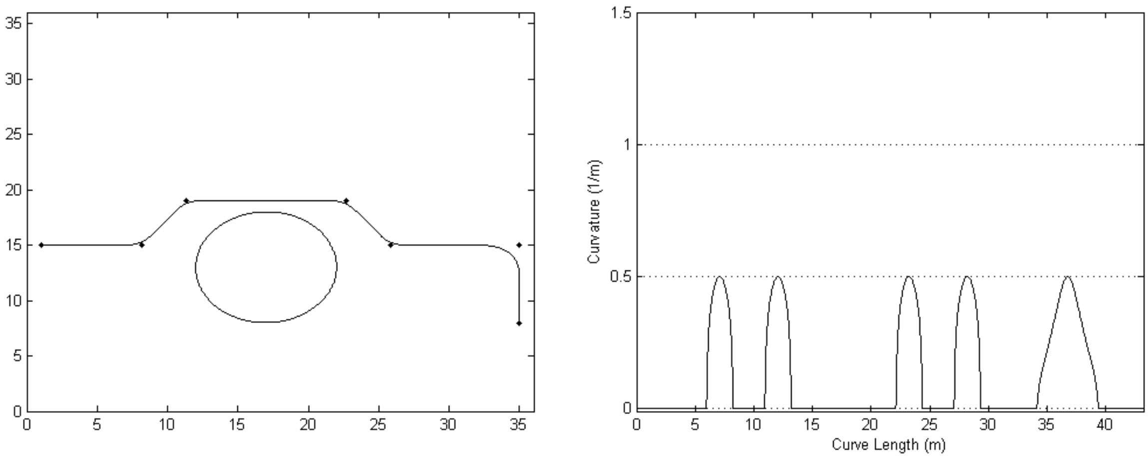

Figure 3 – Path and curvature - Case I

5.2 Case II

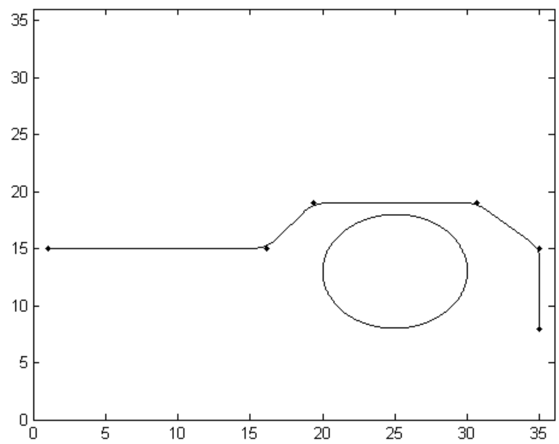

Figure 4 - Path - Case II

5.3 Case III

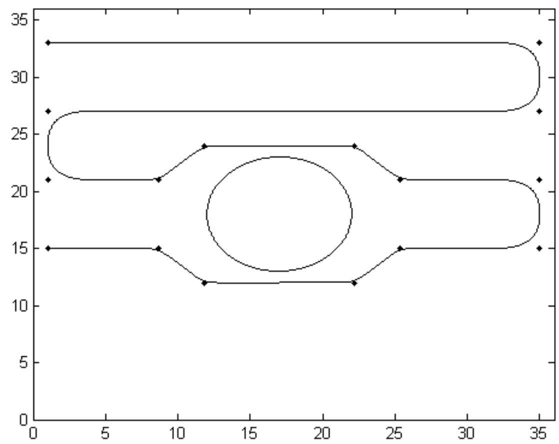

Figure 5 - Path - Case III

5.4 Case IV

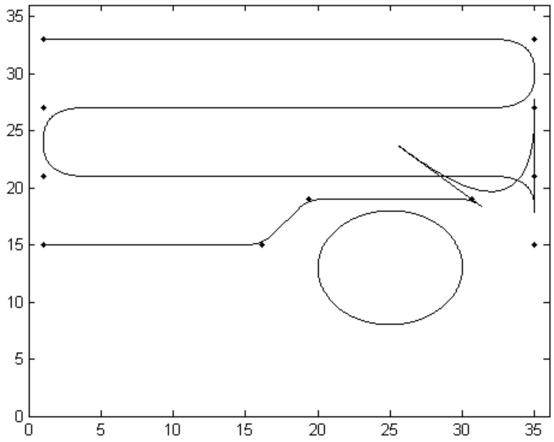

Figure 6 - Path - Case IV

5.5 Case V

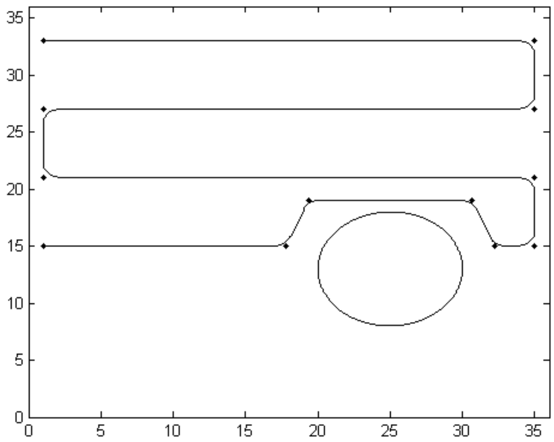

Figure 7 - Path - Case V

6. DISCUSSION

The five cases presented in the last section show the main characteristics of the proposed strategy.

The Case I is the most basic, it has three waypoints and an obstacle located between the first two waypoints. It is possible to see that the vehicle is capable of avoiding the obstacle and go back to its original path. The curvature is limited to the specified value.

The Case II is similar to Case I, but the obstacle is closer to the second original waypoint. The intermediary waypoint $\boldsymbol{W_3}$ was removed, thus allowing the generation of a path that satisfies the vehicle constraints.

In Case III the waypoints are arranged in a lawnmower pattern. The behavior is pretty similar to Case I, with exception of the larger number of waypoints.

It was not possible to generate a feasible path for Case IV with the maximum curvature of 0,5 m^{-1}. If the maximum curvature is increased to 1 m^{-1}, it is possible to avoid the obstacle, as seen in Case V.

The proposed strategy has shown to be very efficient and its implementation was relatively easy. The use of G2CBS allows the generated paths to be curvature continuous and limited to a certain value, besides that, it is possible to determine if a path is feasible or not. A possible inconvenient due to the proposed strategy is that the vehicle will only pass by the first and the last waypoints.

The main limitation of the strategy is considering only circular obstacles. It is not possible to represent obstacles that have one dimension much larger than the other, for example, a wall.

The proposed strategy is adequate to be used as a local path planner, but it still depends on another global planner to generate the initial waypoints.

7. CONCLUSIONS AND FUTURE WORKS

This paper has presented a simple strategy for collision avoidance with previously unmapped obstacles. The strategy consists of generating waypoints around the obstacle and smoothing the path using cubic Bézier spirals, thus obtaining a smooth curve with continuous and limited curvature.

The biggest limitations of the strategy are considering only circular obstacles, and not allowing a variable maximum curvature. It is also dependent on a global planner to generate the initial waypoints.

Some suggestions for future works:

- Allowing variable maximum curvature. For this the speed of the vehicle must be planned for the whole path, as shown in (Sprunk, 2008). The present strategy considers the speed constant;
- Including other types of obstacles, for example, elliptic or polygonal;
- Expand the strategy for a tridimensional environment;
- Test the strategy in an actual vehicle;

8. ACKNOWLEDGEMENTS

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10. RESPONSIBILITY NOTICE